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The sedimentology and palaeoecology of the Westleton Member of the Norwich Crag Formation (Early Pleistocene) at Thorington, Suffolk, England

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Abstract – Extensive sections in the Thorington gravel quarry complex in eastern Suffolk include the most complete record to date of sedimentary environments of the Westleton Beds Member of the Norwich Crag Formation. New palaeoecological and palaeomagnetic evidence is presented, which confirms that the Member was deposited at or near a gravelly shoreline of the Crag Sea as sea level fluctuated during a climatic ameloriation within or at the end of the Baventian/ pre-Pastonian 'a' Stage (Tiglian C4c Substage).

1. Introduction

The gravel quarry complex at Thorington (TM 423 728) is situated 8 km west of Southwold in northern Suffolk (Fig. 1). This paper will present details of observations in the quarry during the period from June 1994 to September 1997, which provide significant biostratigraphical and sedimentological evidence for depositional environments associated with the Westleton Beds Member of the Early Pleistocene Norwich Crag Formation.

The deposits have been exploited in two main phases. The 'north pit' (Fig. 1) was worked from 1992 until early 1995, yielding continuous faces over 50 m long and 10 m in height. However, recent exposures have been limited to smaller excavations in the 'south pit.' Our attention was drawn to this site by B. M. Funnell and D. Hallam (University of East Anglia).

A schematic log of the stratigraphy of the sediments exposed in the Thorington Pit is given in Figure 2, with more detailed facies logs in Figure 3 and lithological counts in Table 2. At Thorington, the upper parts of the Norwich Crag Formation are deformed by the development of active layer (permafrost) structures correlated with the widespread Barham Arctic Structure Soil (Murton, Whiteman & Allen, 1995; Kemp, 1985; Rose *et al.* 1985a) and a later, more arid phase of permafrost conditions that occurred immediately before the deposition of glacial deposits of the Lowestoft Formation in the Anglian Cold Stage (Hart & Boulton, 1991; Kemp, Whiteman & Rose, 1993). The palaeoenvironmental significance of the glacial and periglacial deposits that are exposed at Thorington Pit is discussed elsewhere (Richards, in press).

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2. Late Pliocene to Early Pleistocene deposits in Suffolk

A stratigraphical table, comparing British nomenclature with that of the Netherlands, is given in Table 1.

The earliest Pleistocene deposits that occur in northern Suffolk are the East Anglian Crags, which were deposited at the margins of the southern North Sea Basin. In the study area the Norwich Crag Formation of Funnell & West (1977) can be distinguished from the shelly sands of the Red Crag Formation (Mathers & Zalasiewicz, 1988; Zalasiewicz *et al.* 1988). The Norwich Crag Formation comprises fine- to medium-grained, well-sorted, micaceous sands with a maximum total thickness of 40 m (Hamblin, 1992). Gibbard & Zalasiewicz (1988) and Zalasiewicz *et al.* (1991) recognized four stratigraphical units within the Norwich Crag Formation: the Chillesford Sand; the overlying Easton Bavents Clay and Chillesford Clay, which are geographically separated clay units thought to be of the same age; and the Westleton Beds (Prestwich, 1871), which are well-sorted, clast- to matrix-supported gravels dominated by well-rounded, high-sphericity, chattermarked flint pebbles and cobbles (Hey, 1967).

The lowest part of the Norwich Crag Formation, the Chillesford Sand Member, was deposited in shallow marine conditions during the Antian Stage (Gibbard & Zalasiewicz, 1988; Hamblin *et al.* 1997). Sediments of this age are periodically exposed at Easton Bavents. The deposits are characterized by a temperate mixed forest flora (West, 1961), although vertebrate remains imply that open woodland was also present (Stuart, 1982). The overlying Easton Bavents Clay and Chillesford Clay members were analysed by Zalasiewicz *et al.* (1991), who concluded that they

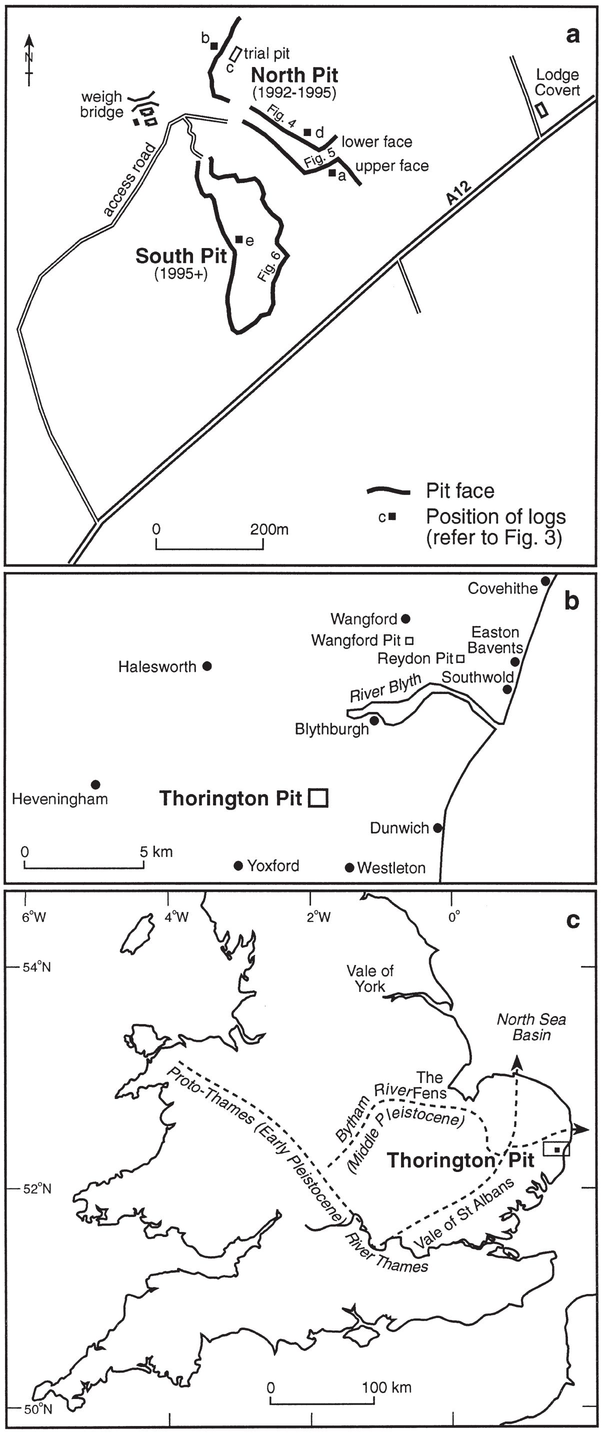

Figure 1. Location of the study area. (a) Location of sedimentary logs and diagrams included in Figures 3, 4, 5 and 6. (b) Location of Thorington Gravel Pit and sites referred to in the text. (c) The position of major drainage systems that affected East Anglia during the Early and Middle Pleistocene and locations referred to in the text.

shared a common provenance. Both units are characterized by pollen, foraminifera and mollusc assemblages that suggest cold stage conditions and falling sea level (Funnell & West, 1962; Norton & Beck, 1972, West & Norton, 1974; West, 1961; West, Funnell & Norton, 1980). Both Hey (1967) and West (1980) suggested that the deposits may have formed under the influence of glaciation, on the basis of exotic minerals introduced from Britain and/or Scandinavia, although this has been questioned in later studies (e.g. Zalasiewicz *et al.* 1991).

Hey (1982) concluded that the gravels of the Norwich Crag Formation may have been supplemented by material introduced by both the ancestral Thames and a precursor to the River Trent, whilst Burger (pers. comm. 1991) suggested that the exotic heavy-mineral component may have been derived from the Baltic River system. Sinclair (1990) proposed that northerly-derived flint pebbles and 'Rhaxella chert' from the Corallian of Yorkshire were transported into the Crag sands by longshore drift. Later, Hamblin *et al.* (1997) suggested that intervening estuaries would have prevented longshore transfer of material. They proposed that the Westleton Beds and intervening clay units, notably at Easton Bavents, Covehithe and Thorington, formed under the influence of the ancestral Trent Bytham River, flowing from the English Midlands. Hamblin *et al.* (1997) believe that the Bytham River ran through southern East Anglia parallel to the River Thames, in which the estuarine Chillesford Clay of the Norwich Crag Formation south of the study area was deposited.

The Westleton Beds occur as planar cross-stratified units, in sets up to 10 m thick, which dip southeast at 10°, as recognized by Hey (1967). He suggested that a modern analogue for these deposits is represented by the prograding beach-face deposits formerly exposed in excavations in the Dungeness beach plain (Hey, 1966). Subsequently, Mathers & Zalasiewicz (1996) subdivided the Westleton Beds into three facies associations. The first, large-scale cross-stratified association represents a beach-face deposit. This association grades into a second, offshore, horizontally bedded sand association, which in turn is replaced in a seaward direction and is incised into by the products of high-energy, channellized rip-current deposits.

Apart from the impressions of marine shells reported by Spencer (1967), no lists of Quaternary fauna or flora occur in the literature for the Westleton Beds. Hamblin *et al.* (1997) reported Carboniferous, Jurassic, Late Cretaceous and Palaeogene palynomorphs from fine-grained clay beds from within the Westleton Beds exposed at the Thorington gravel quarry complex. Their samples yielded insufficient Quaternary pollen to indicate environment or age, although the authors suggest that the altitude and depositional environment of the Westleton Beds precludes deposition during the Antian/Bramertonian marine transgression, as previously suggested by Funnell, Norton & West (1979). In common with Hey, Mathers & Zalasiewicz (1988), they favour emplacement during the Baventian regression, but under the influence of the ancestral Trent Bytham River (Rose, 1994).

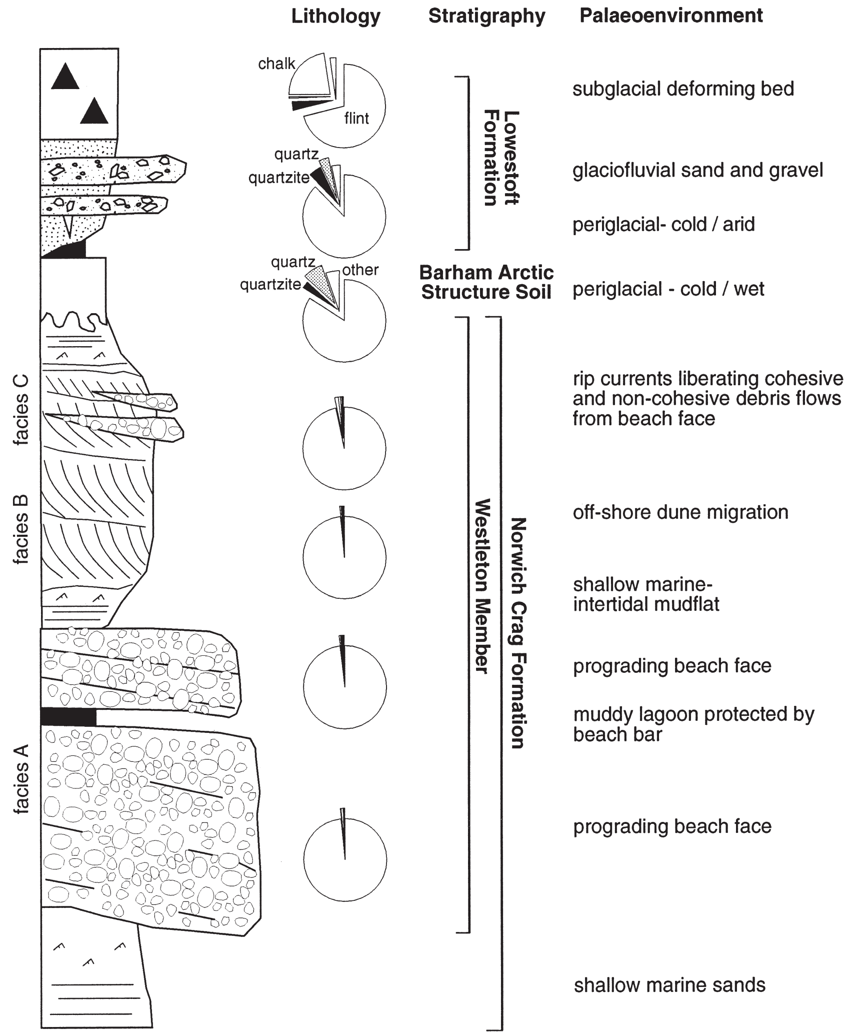

Figure 2. The inferred palaeoenvironments and stratigraphy of the sediments exposed in the Thorington gravel quarry complex, northern Suffolk.

3. The Norwich Crag Formation at Thorington

The lowest sections in the gravel quarry complex are dominated by units of the Norwich Crag Formation. The bulk of these deposits consist of gravels, sands and intervening finer-grained deposits of the Westleton Member. The sections in the member occur between 11 m and 18 m OD (Fig. 3), and present a detailed record of depositional environments associated with the unit.

3.a. Sedimentology

3.a.1. Unit 1

A trial pit in the north pit (TM 4227 7296; August 1994) revealed 2.85 m of fine- to medium-grained, dark-green to yellow sands (Fig. 3). The unit includes plane and wavy stratification and flaser bedding marked by silty-clay drapes within ripple-drift cross-stratification. Rare planar cross-stratified units indicate palaeocurrents towards 015–050°. The unit includes iron pans, poorly developed concretions, and worm-burrow fills, and is traversed by a system of high angle normal faults with throws of 1–4 cm. These deposits comprise sands of the Norwich Crag Formation of Funnell & West (1977), Mathers & Zalasiewicz (1988) and Zalasiewicz *et al.* (1988).

3.a.2. Unit 2

Up to 4 m of well-rounded, flint-rich gravels overlie a channellized contact with the Norwich Crag Formation sands, at 8.2 m OD. The stratigraphical relationships, sedimentology and lithological composition of these gravels suggest that they form part of the Westleton Beds Member (Prestwich, 1871), which are widely reported to overlie directly the sands of the Norwich Crag in northeast Suffolk (Hey, 1967; Mathers & Zalasiewicz, 1996). The vertebrate remains collected from these sediments are listed in Table 3, and the lithological composition is recorded in Table 2. At Thorington Pit, the Westleton Beds Member may be subdivided into an upper and lower unit on the basis of a marked change in bedding orientation (Figs 3, 4).

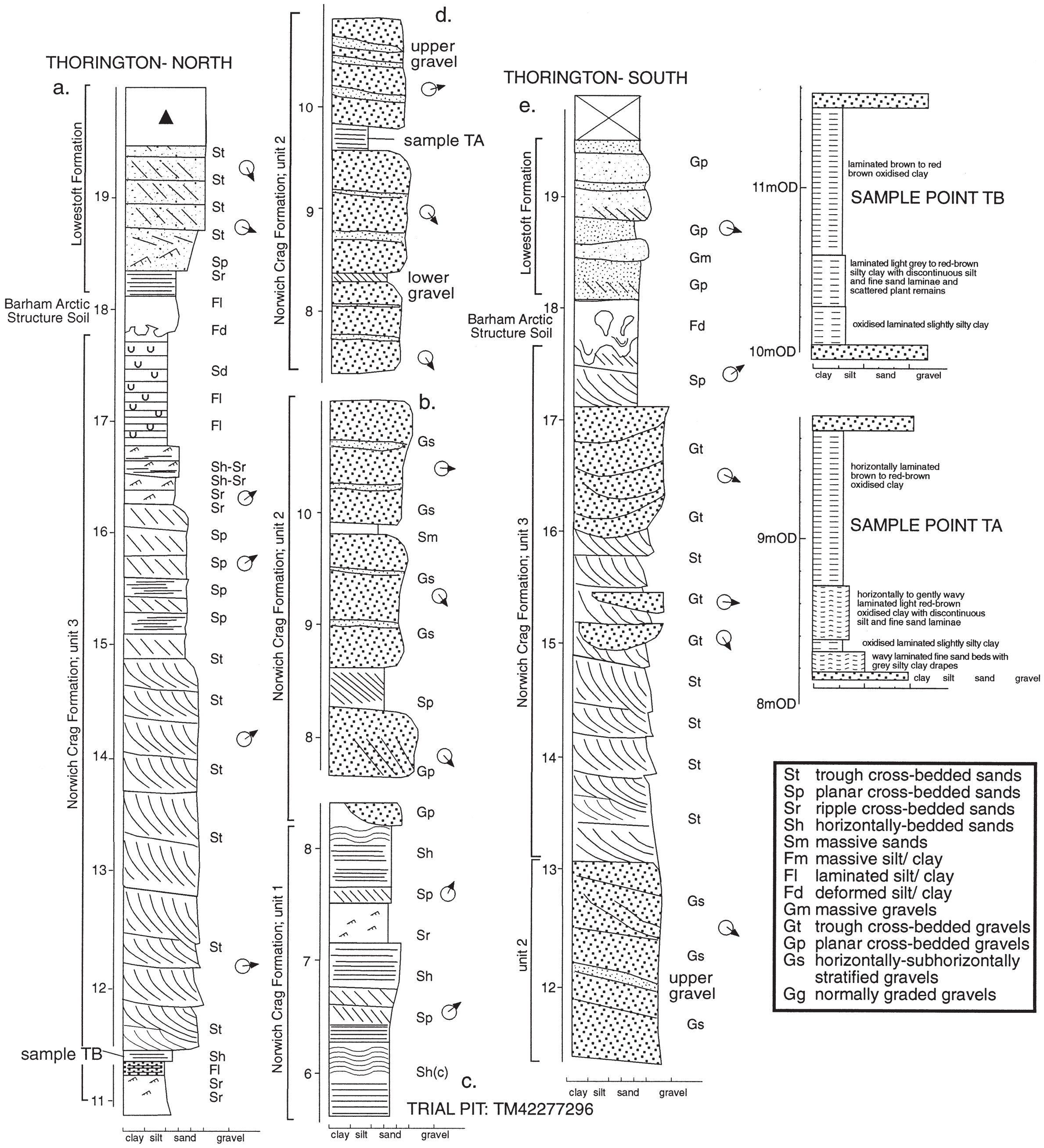

Figure 3. Composite facies logs for the south and north pits at Thorington.

The lower gravels of the unit consist of clast-supported, flint-dominated gravels with sand interbeds that form massive planar foresets 10–50 cm in thickness, inclined at 6–10° towards 085–130°. Prominent reactivation surfaces mark subtle variations in dip angle and/or orientation throughout association A (Fig. 4). Gravel units are dominated by sub-rounded to well-rounded flint pebbles. These generally massive units exhibit crude imbrication, mostly down-dip, although locally up-slope. Normally-graded open-work lenses and planar cross-bedded units occur within the foresets of the association. The bedding is often characterized by textural variations and/or shape-sorting between beds and locally defined by thin (5–25 cm), persistent beds or lenses of plane-stratified medium- to coarse-grained sand. Sand interbeds have conformable to gently concave lower contacts, and bedding is approximately normal to the dip of the gravel units, although a large interbed (Fig. 4) exhibits trough cross-beds, which indicates palaeocurrents toward 156–172°. Sand interbeds increase in number towards the northeast in the north pit, composing nearly 50 % of the lower gravel unit.

The transition to the upper gravel is marked by a change in the orientation of forset units towards 060–095°. The upper gravel body has a wavy, erosive contact with the lower gravel in the northern section of the north pit, marked locally by the occurrence of a coarse

Table 1. The British Quaternary stratigraphic nomenclature and equivalent stages in the Netherlands

Marine oxygen isotope stages	British Isles	Netherlands
1	Flandrian	Holocene
2–5d	Devensian	Weichselian
5e	Ipswichian	Eemian
6		Waarthe
7	Wolstonian/Ilfordian	Saale/Drenthe
8		Drenthe
9		Domnitz
10	Hoxnian	Fuhne
11		Holsteinian
12	Anglian	Elster
13		
14	Cromerian	
15		Cromerian IV
		Nordbergum
16		Glacial C
17		Interglacial III
		Rosmalen
18		Glacial B
19		Westerhoven
		Interglacial II
20		Glacial A
21		Waardenburg
		Interglacial I
22		Bavelian
		Menapian
		Waalian
		Eburonian
	Beestonian	
	Pastonian	
64?	Pre-Pastonian/	C%
	Baventian	C4c
	Bramertonian/	Tiglian
	Antian	C3
	Thurnian	B
	Ludhamian	A
103	Pre-Ludhamian	Praetiglian
104	Pliocene	Pliocene

Table 3. Vertebrate finds at Thorington

Proboscideans	
Anancus arvernensis	gomphothere mastodont
Archidiskodon meridionalis	elephant
Perissodactyls	
Equus stenonis	horse
Artiodactyls	
Eucladoceros sedgwicki	deer
Gazella anglica	gazelle
Cetacea	
Whale	species unidentified
Delphinus delphis	dolphin

Collected by Mr R. Mutch at the basal lag gravels of the Westleton Beds Member (unit 2) of the Norwich Crag Formation sands, Thorington

gravel lag overlain by a plane-stratified silty sand unit (Fig. 4). Elsewhere, the contact is marked by a lenticular bed of laminated grey to brown silty clay, up to 70 cm thick, occurring at 9.3–9.6 m OD. Samples for pollen analysis (see below) were collected at sample point TA (Fig. 3). Elsewhere the contact between the two gravel bodies is less distinct and apparently gradational. However, the upper gravels contain rare, relatively thin (2–10 cm) sand beds within subrounded to well-rounded flint gravels, which exhibit large-scale cross-stratification towards 070–100° at 8–12°. Both up- and down-dip imbrication is evident within the gravel units.

3.a.3. Unit 3

At 10.9 m OD, a planar erosional contact marks a transition into two units composed of fining-upward sequences of fine sand and laminated silt and clay beds, which are separated by up to 6 m of orange to pale yellow medium- to coarse-grained cross-bedded sand (Fig. 3).

Sections in the north pit in 1994–5 exposed large-scale, tangentially-based tabular, trough, and festoon cross-bedding (facies Sp, St). Sets vary in thickness from 30 cm to 70 cm. Gravels occur as lenticular beds, and also occur as thin, laterally impersistent pebbly lags between sets (at first and second order bounding surfaces), and within sets (reactivation surfaces and slipfaces of individual cross-sets). Three major bounding surfaces are prominent, dipping at 1–3° towards 352–025°, and palaeocurrents measured from trough axes and planar cross-beds indicate flow directions towards 040–100° (Fig. 5). In the south pit, the upper part of the unit includes isolated lenticular beds, and stacked units of channellized, sub-rounded to well-

Table 2. Lithological composition (8–16 mm fraction) of sediments exposed at Thorington

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Flint	97.9	98.5	98.5	98.3	98.0	98.2	96.7	96.4	96.8	84.2	87.6	88.2	71.2	93.0
Quartz	0.4	0.5	0.3	0.6	0.6	0.3	1.3	1.8	1.1	2.6	3.0	6.7	3.2	1.4
Quartzite	0.8	0.5	0.3	0.6	0.3	0.6	1.0	0.8	0.7	7.9	4.5	3.5	0.7	1.4
Chert	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.7	1.9	1.8	0.4	0.4	1.0
Sandstone	0.0	0.2	0.3	0.3	0.3	0.3	0.0	0.0	0.0	2.6	1.5	0.0	0.7	1.0
Limestone	0.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.4	0.5
Chalk	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.5	0.0
Ironstone	0.0	0.0	0.3	0.0	0.3	0.3	0.7	0.3	0.4	0.0	0.0	0.0	0.0	0.0
Ign/meta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.8	0.7	1.0
Other	0.4	0.2	0.5	0.3	0.3	0.3	0.0	0.3	0.4	0.4	0.6	0.4	0.4	0.7
No.	238	407	399	347	352	327	304	367	277	266	330	254	285	415

1–2, Westleton Member, unit 2, association A; 3–4, unit 2, association B; 5–6, Westleton Member, unit 3 (pebbly sands); 7–8, unit 3 (channelized gravels); 9, gravels within Barham Arctic Structure Soil; 10–12, Lowestoft Formation gravels; 13, Lowestoft Formation, unweathered diamicton; 14, Lowestoft Formation, weathered diamicton.

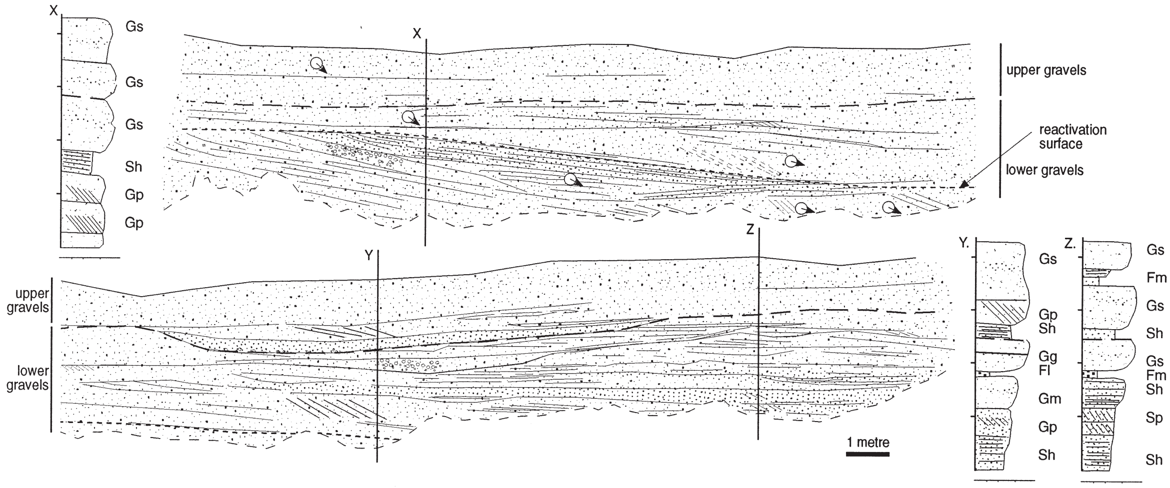

Figure 4. Detail and facies logs of unit 2 of the Westleton Member, north pit, Autumn 1994 (for abbreviations see key in Fig. 3).

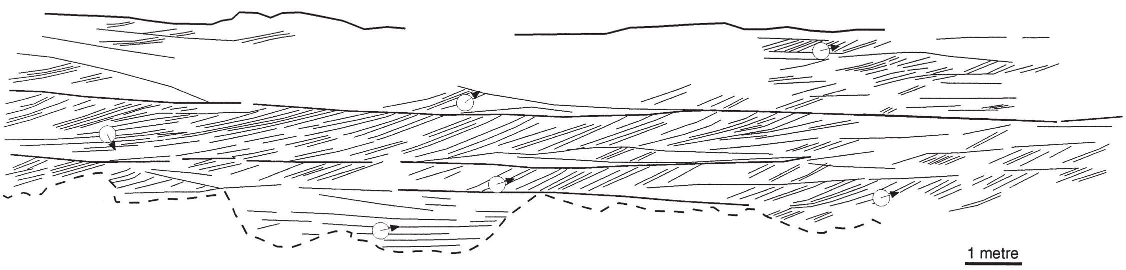

Figure 5. Detail of unit 3 of the Westleton Member, large-scale, subaqueous sandy bedforms exposed in the north pit, Autumn 1994.

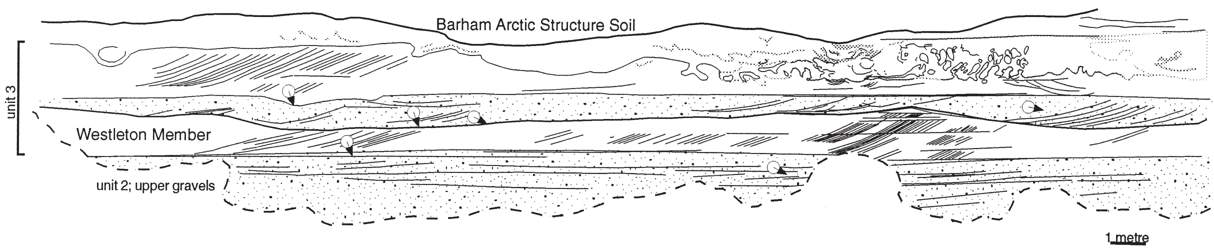

Figure 6. Detail of units 2 and 3 of the Westleton Member and the Barham Arctic Structure Soil, south pit, Spring 1997.

rounded flint-rich gravels (Fig. 6), in beds up to 50 cm in thickness, comprising fining-upward sequences of massive, trough cross-bedded, and normal- and inverse-graded gravels. The stacked units have a wavy, channellized base and have a lateral extent of 25 m through the section. The channellized gravel units are overlain by up to 2.5 m of tabular and trough cross-bedded sand sets 30–60 cm in thickness. The lithological composition and shape characteristics of gravel samples from this unit is similar to those of the gravels of unit 2 (Table 3).

The lower fine unit consists of horizontally bedded fine- to medium-grained sand and wavy to ripple cross-bedded fine- to medium-grained sand. Form sets within the rippled sand exhibit marked symmetry (ripple indices: 5–7.5; ripple symmetry indices: 1.09–1.33), and opposed cross-bedding, chevron and bundled upbuilding is evident. Locally, the ripple cross-bedded sand passes upward into horizontally laminated silt and clay units with laterally impersistent, fine-sand laminae. This bed was originally observed and sampled for palaeomagnetic analysis by B. M. Funnell and D. Hallam in 1993. Samples for palaeobotanical analysis were collected from point TB, as shown in Figures 3 and 7a. The results are presented below.

The upper fine unit forms a fining-upwards sequence from horizontally bedded medium-grained sands to finer units containing wavy and symmetrical to asymmetrical ripple cross-bedding, and apparently massive silty sand and silt units, or laminated silt and clay beds. Mud drapes within foreset beds, flaser and convolute bedding are present in the upper fine unit. In the north pit, the laminated silt and clay unit is up to 100 cm in thickness, although its upper portions are

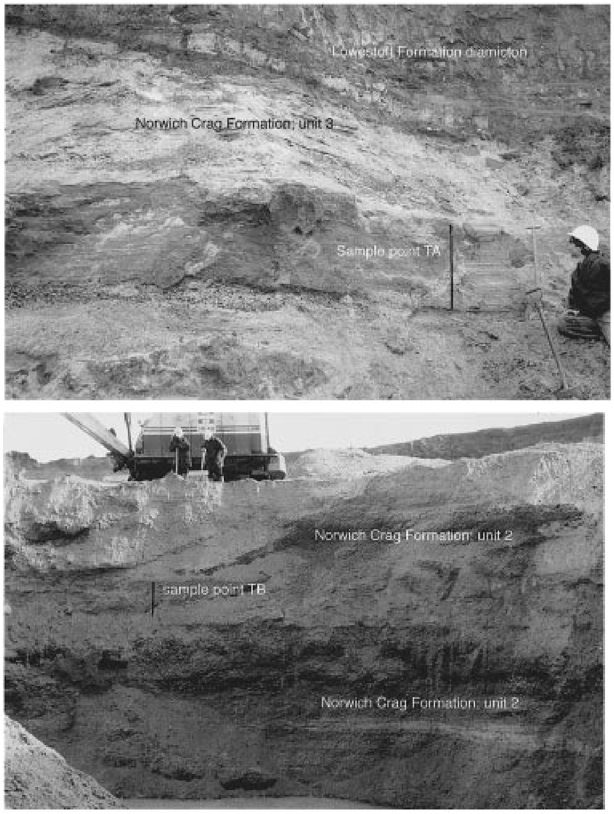

Figure 7. (a) Sample point TA, Thorington gravel quarry complex. (b) Sample point TB, Thorington gravel quarry complex.

often truncated by the Barham Arctic Structure Soil. In the south pit, the upper laminated silt and clay unit is up to 1.6 m thick, and is erosively overlain by coarse-grained glaciofluvial gravels of the Lowestoft Formation. Locally, clay beds contain cracks and tapered veins that are infilled with fine sand. The clay units between these veins form lenticular units that are concave upwards.

3.b. Palaeobotany

3.b.1. Palynology

Samples for pollen analysis were collected from profiles TA and TB in the fine sediments of unit 2 described above(Figs 3, 7a, 7b). They were prepared using standard chemical methods (West, 1977), and modified using sodium pyrophosphate (Bates, Coxon & Gibbard, 1978). Pollen type nomenclature follows Andrew (1970), together with some types listed in Birks (1973). The pollen diagram from profile TB (Fig. 8) and counts from site TA (Table 4) have been calculated on the basis of percentages of total land pollen and spores, excluding aquatic taxa. The latter, together with pre-Pleistocene taxa, are calculated as a percentage of total palynomorphs.

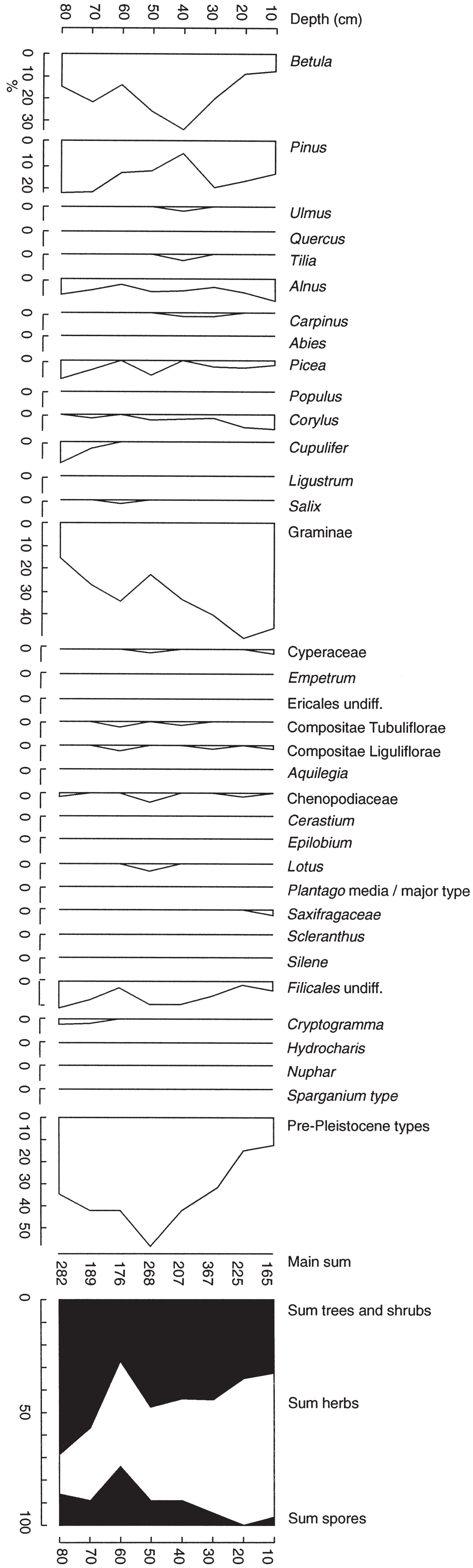

Figure 8. Pollen diagram from sample TB, Thorington gravel quarry complex.

Table 4. Pollen analysis from samples TB and TC

%	B: 30 cm	B: 40 cm	B: 50 cm	C: 15 cm	C: 20 cm
Betula	8.3	10.6	11.9	7.4	
Pinus	27.2	34.4	47.7	77.8	70.0
Alnus	5.8	3.3	4.6		
Carpinus	0.8				
Ostrya			2.0		
Picea	6.6	5.3	4.6		
Corylus	3.3	1.8			
Salix		0.7			
Cupulifer	2.5	9.9	8.3	3.7	
Gramineae	31.4	24.5	9.2	7.4	30.0
Comp. Lig.	2.5	3.7			
Comp. Tub.	0.8				
Chenopodiaceae	2.5	1.3			
Scleranthus		0.7	1.8		
Filicales	1.7	3.3	0.9		
Cryptogramma	6.6	4.0	9.2		
Azolla			0.7		
Lemna				3.2	
Pediastrum				3	9.1
Reworked types	26.6	30.7	35.1	9.7	
Main sum	121	151	109	27	10
Sum trees and shrubs	54.5	66.2	78.9	88.9	70.0
Sum herbs	37.2	26.5	11.0	11.1	30.0
Sum spores	8.3	7.3	10.1		

The pollen spectra from sample TA and TB, although from different locations in the transition from sediments of unit 2 to unit 3, are generally well preserved and very similar. They will therefore be discussed together and minor differences noted. The spectra can be grouped into a single Gramineae–*Betula*–*Pinus* pollen assemblage biozone (pab). Despite substantial changes in the frequency of certain taxa, tree pollen consistently represents 40–79 % of the total land pollen. All levels in the diagram from TB (Fig. 8) are dominated by Gramineae pollen, but the counts for site TA (Table 4) show lower, although still significant, frequencies. These high grass frequencies are accompanied by few herb pollen taxa characteristic of dry, partially-disturbed grassland, including *Plantago* major/media type, Compositae (Liguliflorae), *Scleranthus*, *Lotus* and *Cerastium*. The pollen of marsh and aquatic vegetation, associated with the pond itself, include *Nuphar*, *Hydrocharis*, *Azolla* and *Sparganium* type. The high frequencies of reworked pre-Pleistocene palynomorphs found throughout emphasize the volume of freshly eroded material entering the water-body (cf. Riding *et al.* 1997). The upward decrease in this inwash indicates infill of the basin and colonization of newly emergent surfaces by plants, particularly Gramineae.

Tree pollen are dominated by *Pinus*, but *Betula* is also important, whilst *Alnus* is the only other tree pollen present in numbers that suggest local growth of this tree. The abundance of *Filicales* spores may be associated with alder carr in this situation. Pollen of *Carpinus*, *Quercus*, *Ulmus* and *Fraxinus*, to judge from their low numbers, either represent trees growing distant from the site or are reworked.

Minor variations in the diversity of the assemblages, and particularly the content of *Pinus*, may reflect differences in water depth or distance from the basin margins, but most likely are due to minor changes in current and sediment transport. In this context it is important to consider the taphonomy of the pollen assemblage. The large proportion of pre-Pleistocene material, mainly inwashed from a westerly direction by stream transport (Riding *et al.* 1997), may indicate a similar derivation for some of the Pleistocene taxa. However, their better preservation and the ecological consistency of the assemblage makes this unlikely.

The Chenopodiaceae in both samples suggests proximity to coastal saltmarsh. However, overall the assemblages recorded from both TA and TB are typical of a freshwater pond, or a small lake with local fringing vegetation of marsh and aquatic plants into which material was being washed, possibly from a stream or river. By contrast coniferous woodland dominated the drier areas, with an understorey of ericaceous shrubs and *Cryptogramma*, suggesting acid soils locally. The change in the spectra through the sequence is slight and may indicate local seral, rather than climatic, change.

The lack of substantial compositional change in the spectra prevent confident correlation with events known from elsewhere. The highly restricted assemblage in both beds is typical of that recovered from cool to cold stage events in the Early Pleistocene marine sequences in East Anglia. Here assemblages dominated by *Pinus*, accompanied by substantial quantities of Gramineae and often also accompanied by Ericales, are very common (West, 1980). However, the occurrence of *Picea*, *Alnus* and *Corylus*, together with very low numbers of mixed oak forest genera (e.g. *Ulmus*, *Quercus*, *Tilia* and *Carpinus*) suggest conditions were not as severe as during the early part of the Baventian/?pre-Pastonian 'a' Stage, where assemblages contained far lower diversities (Zalasiewicz *et al.* 1991). The assemblage possibly represents conditions intermediate between those of the extreme cold typified by that of the Baventian (that occurs in sediments that stratigraphically underlie these sediments) and full interglacial conditions (cf. West, 1980), that is, they could represent an interstadial-type event in which boreal-like forest flourished in the hinterland, but with grassland-dominated communities on the coastal sand areas adjacent to the locality.

The spectra are consistent with, but not directly indicative of, a pre-Pastonian 'a' age to which the Westleton Member is generally assigned.

3.b.2. Plant macrofossils

A sample was collected from the 20–35 cm level at site TA for plant macrofossil analysis. In the laboratory the whole sample was taken and disaggregated in cold water. It was then washed through a nest of sieves down to 150 μm mesh size. Macroscopic plant remains were then picked from the residue and identified. The nomenclature follows *Flora Europaea* (1964–93). The results are given in Table 5.

The assemblage recovered is of limited diversity, but was well preserved. It predominantly comprises plants of open dry grassland including *Plantago* cf. *media* and *Polygonum lapathifolium*, while *Scleranthus* cf. *annuus* indicates local sandy and gravelly surfaces. A second group of plants are those of open ground, pond margins and ditches, and include *Bidens tripartita*, *Eleocharis palustris/uniglumis*, while the *Juncus* seeds also originated from parent plants growing in local marsh. The salt-marsh plant *Chenopodium bitryoides/rubrum* indicates salt water in the vicinity. Submerged plants are represented by the aquatic alga *Chara*. Finally, the single find of an *Alnus* fruit confirms the pollen evidence for local stands of this tree.

The plant macrofossils indicate that the sediments were deposited in a standing water environment. The over-representation of waterside, damp ground and aquatic taxa suggest that the assemblages are dominated by material from in or immediately around the water body. For this reason it is difficult to comment on the regional environment, although the plant macrofossil assemblage indicates temperate conditions; many of the plants are still growing in Suffolk today, with the exception of *Picea* and *Cupulifera*. Indeed the plant macrofossil assemblage complements the interpretations derived from the pollen assemblages presented above, that the vegetation is typical of a cool environment undergoing climatic amelioration, with small plants reacting more quickly to the ongoing temperature changes.

Table 5. Plant macrofossils from site TA level 35 cm in Thorington

Trees		
Alnus sp.	fruit	1
Herbs		
Plantago cf. *media*	seed	1
Sclenanthus cf. *annuus*	fruit	1
Polygonum lapathifolium	nut	1
Bidens tripartita	achene	3
Bidens sp.	barbed awns	14
Eleocharis palustris/uniglumis	nut	1
Herbs/ Shrubs		
Chenopodium botryoides/rubrum	seed	1
Aquatic		
Characae	oospores	11
Unclassified		
cf. *Eleocharis* sp.	nut	1
Juncus sp.	seed	1
Ranunculus sp.	achene	1
Miscellaneous		
Beetle	wing case	1
Foraminiferid		1
Fungae	sclerotia	1
Leaf	margin	1
Moss	stem with leaves	1
Woody fragments	(unidentified)	10
Total weight of sample	200 g	
Volume	115 cm^3	

3.c. Vertebrate remains and palaeomagnetic analyses

The vertebrate remains recovered from the sands and gravels of unit 2 in the Thorington gravel quarry complex between 1991 and 1995 are shown in Table 3. The vertebrate fauna is similar to that recorded from the Norwich Crag Formation deposits elsewhere (Spencer, 1971). Of principal palaeoenvironmental significance is the occurrence of whale and dolphin remains. While dolphin remains have not been recorded elsewhere, whale vertebrae have been recovered from the Norwich Crag Formation in cliff sections at Southwold and Walberswick, and also from former gravel pits at Holton (Spencer, 1971).

The lower fine unit of unit 3, which was sampled for pollen analysis (sample TA), was deposited during an episode of normal magnetic polarity (D. Hallam, unpub. Ph.D. thesis, Univ. East Anglia, 1995), consistent with the Late Baventian/pre-Pastonian 'a' age suggested on other criteria.

4. Discussion: depositional environments and stratigraphical significance

The markedly rounded shape of the gravel clasts and the sedimentary structure of unit 2 suggests that the gravels are the product of a prograding beach face, with modern analogues at Dungeness, Orfordness, Sizewell and Chesil Beach (Hey, 1967; Carr, 1971; Hart & Plint, 1989; Mathers & Zalasiewicz, 1996). These gravels accumulated at the margins of the Early Pleistocene Crag Sea. The elevation of these gravels with respect to modern sea level may be a function of local tectonics. The southern North Sea Basin has undergone active subsidence throughout the Quaternary period, and areas marginal to this subsidence have been uplifted due to the progressive eastward downtilting of the British landmass on the opening of the Atlantic Ocean (Taylor & Smalley, 1969; Clarke, 1973; Mathers & Zalasiewicz, 1988).

As at Wangford (Westleton Beds facies A of Mathers & Zalasiewicz, 1996), the gravels of the Westleton Member can be subdivided into an upper, more steeply dipping subfacies, and a lower, shallow-dipping subfacies. However, the variations in foreset-dip direction that occur within the gravels of the Westelton Member at Thorington are likely to be the result of a change in the dominant direction of progradation, rather than relative height within the beach profile, as the generally low dip values suggest that the subfacies were deposited at a similar level in the prograding beach face. Reactivation surfaces within the upper gravel unit probably resulted from less marked change in the angle and direction of beach progradation. There is vertical variation in shape-sorting between adjacent foreset beds, with some facies dominated by 'rods' and 'blades', while other facies are largely composed of 'spheres'. This shape-sorting has been reported from typical beach- and shore-face conglomerates by Bluck (1969) and Dobkins & Folk (1970), and is likely to have promoted the 'up-dip' imbrication noted in some beds. However, gravel foreset beds also exhibit localized cross-bedding. It is possible that both 'up-dip' imbrication and cross-bedding may have occurred in association with localized eddies in storm conditions.

The lenticular bed of grey to brown silty clay, which occurs at the contact between the upper and lower gravels of unit 2, probably accumulated in a body of standing water, protected by surrounding gravel bars high on the beach face, i.e. a lagoon. The palaeobotany of sample TB supports these conclusions, and suggests that the body of water was fed by a low discharge stream, which, on the basis of inwashed palynomorphs (Riding *et al.* 1997), appears to have flowed from a westerly direction. The intercalated sand lenses that occur through the lower and upper parts of the unit may have been blown into the body of water by periodic, high-velocity onshore winds, or may have been brought in by wave activity during storm events. The bed appears to mark an interlude and a cessation of shingle supply during the development of the beach before progradation was reinitiated, in a more northerly direction.

Unit 3 comprises a lower fine-grained unit (facies Sr, Sh Fl; sample TA) overlain by large-scale cross-bedded sand (facies Sp, St), which is in turn overlain by a further fine-grained unit (facies Sh, Sr, Fl, Sd). Bounding surfaces, reactivation and variations within the finer units at the base and top of unit 3 attest to a fluctuating water level throughout the deposition of the unit.

Both the upper and lower fine units that bound the cross-bedded sand facies exhibit sedimentary structures typical of shallow marine, wave-dominated or intertidal environments. The sand-filled veins that truncate the clay laminae in the upper fine unit are thought to represent desiccation cracks. Similar features have been reported from laminated clays exposed at Easton Bavents and Covehithe (Hamblin *et al.* 1997). The palynology of sample TA is again consistent with the input of freshwater into a coastal environment by a river flowing from the west.

The large-scale cross-bedded sands of unit 3 are interpreted here to equate to the Westleton Beds facies B of Mathers & Zalasiewicz (1996), who regarded the planar cross-stratification as the product of wave/storm processes and small-scale cross-sets as indicating offshore transport through the migration of small dunes. While the two-dimensional bedforms are similar to that reported from Quay Lane Pit, Reydon (TM 483 775; Mathers & Zalasiewicz, 1996), the scale of the trough cross-stratification in the northern section at Thorington suggests that offshore dune migration was of greater magnitude than reported elsewhere. The isolated and stacked units of channellized, well-rounded, flinty gravels exposed in the south pit at Thorington probably represent Westleton Beds facies C of Mathers & Zalasiewicz (1996), which they regarded as products of high-velocity, nearshore rip-currents. Massive, normal- and inverse-graded gravel units document both cohesive and non-cohesive/turbulent debris flows from the shore face, which probably occurred during storm events.

In summary, units 2 and 3 record fluctuating, but transgressing, sea level throughout the deposition of the Westleton Beds Member. Palaeoecological and palaeomagnetic evidence suggests that beach progradation, lagoonal, estuarine and off-shore deposition took place under a cool to cold climate, probably during amelioration at the end of the Baventian/pre-Pastonian 'a' Stage. This stage is equated with the Tiglian C4c Substage in the Netherlands sequence (Gibbard *et al.* 1991). The lithological composition of the clast component of both beach gravels and rip-current deposits suggests that both the River Thames and the Bytham River may have provided gravel to the margins of the Crag Sea. On the basis of the lithological compositions recorded in Table 3, it is impossible to suggest which river dominated the gravel supply. The gravel component of the Westleton Beds Member is dominated by flint, and both the Bytham River and River Thames are likely to have excavated Palaeogene outcrops to the west and southwest. Previous inferences regarding the derivation of the gravels has largely relied on the more exotic components within the gravels. This is problematic because of the fact that most shingle beaches have a polycyclic origin; one can-not discount the role of longshore drift in the provision of distinctive 'spicular flints' and other lithologies that may have source areas in Lincolnshire and Yorkshire (Sinclair, 1990).

Although it is practically impossible to determine the morphology of the coast and nature of sedimentary cells that operated in the Crag Sea at this time, the rip-current deposits and the gravelly lags within large, sandy bedforms, which occur in the sequence directly above the prograding beach deposits, bear testament to a high-energy coastal environment capable of the longshore transport of large amounts of shingle both from the beach face and off-shore. It is unlikely that the estuaries that developed at the margins of the Crag Sea would have curtailed these littoral movements, as suggested by Hamblin *et al.* (1997). In addition, much of the gravel that constitutes the Westleton Beds is likely to have been deposited in the off-shore zone during earlier cold stages. Therefore, while the heavy mineralogy and reworked palynomorphs present within the clay beds that are associated with the Westleton Member have been used to determine whether the River Thames or Bytham River was responsible for their deposition, the provenance of the clast component of the Westleton Beds Member is likely to be more complex.

5. Conclusions

The extensive exposure of the Westleton Member at Thorington provides considerable support for previous evidence that it was deposited at a gravelly shoreline (Hey, 1967; Mathers & Zalasiewicz, 1996). All three successive facies described by Mathers & Zalasiewicz (1996) have been exposed in the quarry complex between 1994 and 1997.

The palaeobotany of fine beds that occur within the Westleton Beds Member is consistent with emplacement during a cold stage, although many elements of the plant macro- and micro-fossil assemblage suggest climatic amelioration, perhaps either at the beginning or at the end of a cold stage or during an interstadial. The stratigraphical, palaeoecological and palaeomagnetic evidence presented here suggests that the Westleton Beds are of Baventian/pre-Pastonian 'a' age (Tiglian C4c Substage). The fine beds that occur between two distinct progradational phases in the beach-face deposits appear to have accumulated during a phase of climatic amelioration that might have resulted in sea-level stability and an hiatus in gravel deposition within an episode of generally stable low sea level and abundant sediment supply. The deposition of two further fine beds in intertidal, estuarine environments suggest a fluctuating sea level throughout the phase of marine transgression that was responsible for the deposition of the Westleton Member.

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